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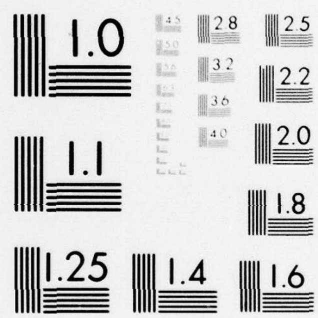

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(9) AIR FORCE SURVEYS IN GEOPHYSICS, NO. 410

(6) # The Current Status of Predictions of Low Energy Plasma Interactions With Space Systems

(10) HENRY B. GARRETT, Capt., USAF

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FOR THE COMMANDER

John Howard

Chief Scientist

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFGL-TR-79-0089	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) THE CURRENT STATUS OF PREDICTIONS OF LOW ENERGY PLASMA INTERACTIONS WITH SPACE SYSTEMS		5. TYPE OF REPORT & PERIOD COVERED Scientific. Interim. 6. PERFORMING ORG. REPORT NUMBER AFSG No. 410
7. AUTHOR(s) Henry B. Garrett, Capt, USAF		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Air Force Geophysics Laboratory (PHG) Hanscom AFB Massachusetts 01731		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 62101F 76610803
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Geophysics Laboratory (PHG) Hanscom AFB Massachusetts 01731		12. REPORT DATE 4 April 1979 13. NUMBER OF PAGES 38
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Spacecraft interactions Space plasma Geomagnetic activity Space forecasting		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The present status of low energy magnetospheric plasma interactions with space systems is reviewed. The role of predictions in meeting user needs in assessing the impact of such interactions is described. In light of the perceived needs of the user community and of the current status of modeling and prediction efforts, it is suggested that for most user needs more detailed statistical models of the low energy environment are required. In order to meet current prediction requirements, real-time in situ measurements are proposed as a near-term solution.		

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Preface

I would like to thank Dr. A. Vampola of Aerospace Corp. who encouraged me to write this review. As always, the comments of Dr. W. Burke and C.P. Pike were invaluable. Mrs. M. Spanos spent many much appreciated hours typing the manuscript. Dr. A.J. Dessler was responsible for most of my knowledge and work in the area of solar-terrestrial predictions. Finally, the facilities available at AFGL made the work represented here possible.

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The Current Status of Predictions of Low Energy Plasma Interactions With Space Systems

1. INTRODUCTION

As we pass from the age of exploration of the near-earth space environment to the exploitation phase, an increasing need has arisen for an understanding of the environmental interactions between space systems, space systems operations, and the low energy (0-100 keV) plasma environment. The problem of concern to the space physics community remains, however, the definition of this environment and how it is perturbed by natural and, increasingly, man-made variations. It has become clear, however, that a careful choice must be made in deciding what parameters—both descriptive and predictive—are necessary to our understanding of the near-earth regime. An important element in this choice that has been largely ignored is the issue of user needs. Much of this review will be based on the perceived needs of the existing and potential user community in this era of space exploitation of the near-earth magnetospheric environment.

In this review, the present status of low-energy plasma modeling and, where necessary, the related issue of the geomagnetic and magnetospheric electric field modeling are covered. In light of the growing role of satellite-environment interactions, this area forms a major part of the review. As an adjunct, current attempts at predicting geophysical and, hence, magnetospheric variations by employing various geomagnetic indicators are discussed. An example is presented

(Received for publication 4 April 1979)

in which all three areas are linked to form a reasonably coherent picture of one phenomena—spacecraft charging in the geosynchronous environment.

The review concludes with a discussion of important areas for future research. In particular, models of a variety of geophysical processes and physical interaction mechanisms are needed in the immediate future. Not only do measurements of the low energy plasma environment need to be expanded, but currently existing data sets must be better organized and exploited. Finally, the necessity for real-time, in situ measurements to establish the current state of the magnetosphere are presented as a near-term alternative to detailed magnetospheric modeling.

2. THE NEED FOR LOW ENERGY PLASMA/SPACE SYSTEMS INTERACTION PREDICTION

Unlike the situation for high energy particle modeling where radiation damage is a known threat or for the neutral particle population where atmospheric drag is a well-recognized problem, the effects of the low energy near-earth plasma environment on space systems are at best subtle (see review by Johnson et al, 1979). It has only been with the advent of the new generation of sophisticated communication and scientific satellites that previously minor systems interactions such as spacecraft charging and surface contamination have become of growing concern to the spacecraft designer and user. In this section, the principal interactions that have come to light are outlined and the associated problem areas from the designer/user standpoint defined.

The principal effect of the low energy particle environment on spacecraft systems is currently believed to be spacecraft charging. Although recognized early as a source of error in low energy particle measurements in the plasmasphere (Whipple, 1965; Whipple and Parker, 1969a, b) and as a potential source of drag (see review by Brundin, 1963), it was not until the observations of significant potentials on the order of -10 kV on the geosynchronous ATS-5 satellite during eclipse (DeForest, 1972) that an interest was really taken in the phenomenon. An example of this phenomenon is given in Figure 1 for the ATS-6 satellite. Likewise, it was not until various satellites (Shaw et al, 1976; McPherson and Schober, 1976) had suffered what were assumed to be logic upsets resulting from arcing between differentially charged surfaces (Figure 2)—and a relationship between arcing and the geomagnetic index a_p (Figure 3) was found— that the user community became concerned enough to support a joint AF/NASA spacecraft charging program. This joint effort recently resulted in the successful launch of the P78-2 (SCATHA) satellite—the first satellite designed to specifically study environmental interactions. The buildup of static charge on satellites (particularly at geosynchronous orbit) by the low energy

plasma not only affects particle measurements, it is believed to generate a wake (Parker, 1977, and references therein) that could be a potential source of plasma waves that could deform structurally weak surfaces such as the solar sail (Douglas et al, 1977). Even the passage of a structure in and out of eclipse can pose a threat, due to potential gradients and current flows (Gauntt, 1979).

The fact that spacecraft surfaces can become charged also contributes significantly to optical surface contamination. As discussed in Cauffman (1973), this is believed to be related to the ionization of outgassed contaminants from the spacecraft which then are reattracted to charged surfaces. Likewise, the fact that a spacecraft is immersed in ionized plasma can lead to problems such as multipacting (Freeman and Reiff, 1979) or power losses in high voltage solar power panels (McCoy et al, 1979).

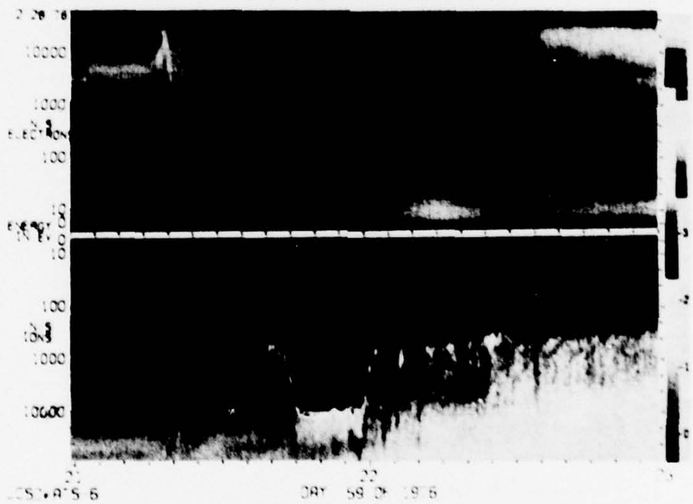

Figure 1. Spectrogram of Day 59, 1976, from ATS-6 (see DeForest and McIlwain, 1971, for explanation of scales). The dropout in the ions between 2145 and 2200 UT occurs simultaneously with satellite entry into eclipse and reflects in eV the negative potential in volts, V, on the satellite as it became charged due to the loss of photoelectrons

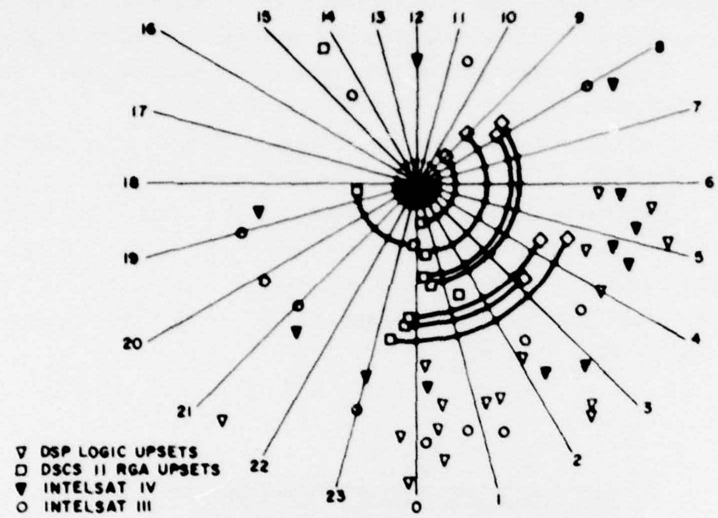

Figure 2. Local Time Dependence of Circuit Upsets for Several DoD and Commercial Satellites (McPherson and Schober, 1976). Radial position has no significance

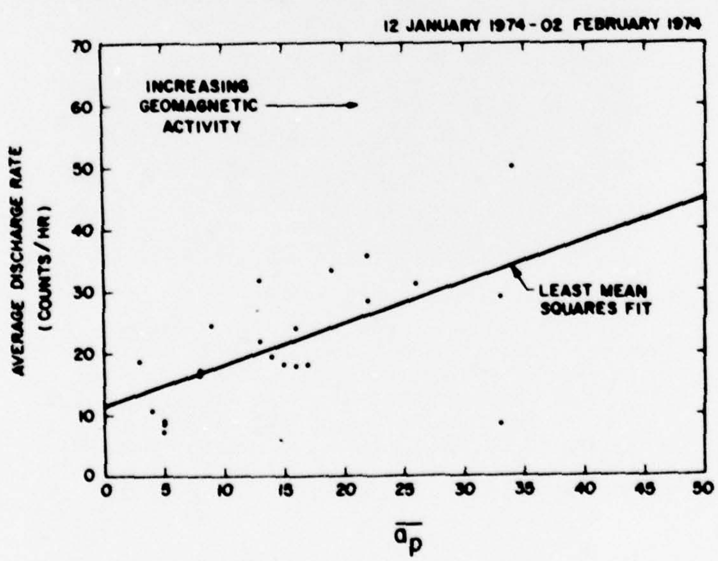

Figure 3. Daily Average Discharge Rate as a Function of Daily Average a_p (from Shaw et al. 1976)

As structures grow significantly in size, the problems just discussed grow in effect and in potential for damage. In Figure 4 we have plotted the predicted growth rate of large structures. Effects such as the $\overline{V} X \overline{B}$ electric fields that are generated in spacecraft, which are now considered only of nuisance value, could easily become significant as structural dimensions grow as projected in Figure 4. More ominous, however, is the potential for such large structures to perturb the environment. At geosynchronous orbit, as an example, Garrett and DeForest (1979a) estimate photoelectron emission rates on the order of 0.4 nA/cm^2 (this is believed to be the flux that actually escapes, not necessarily the total emission rate at the satellite surface). Such fluxes of low energy (~ 10 eV) particles are relatively unimportant in the plasmasphere, but could be potentially damaging in the plasma sheet where they are comparable to the ambient flux and represent a colder plasma component (Garrett and DeForest, 1979b).

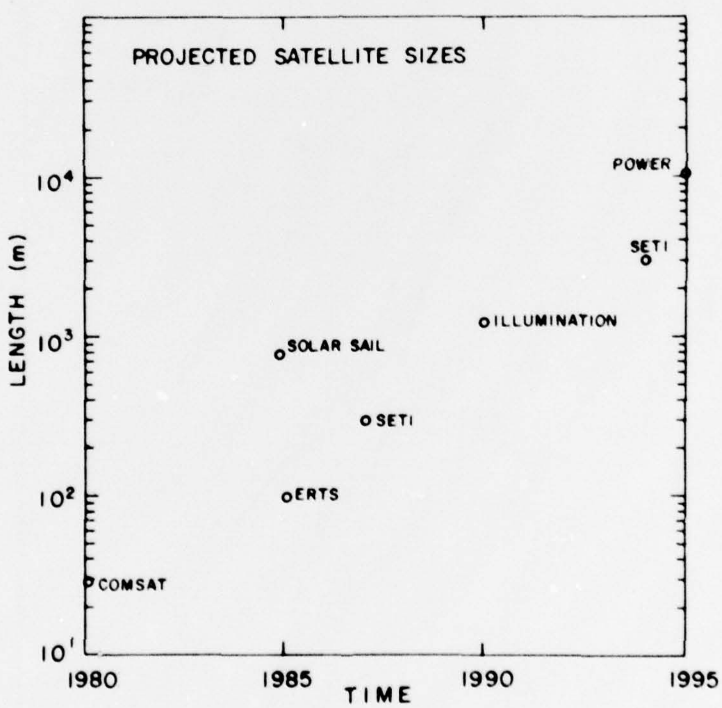

Figure 4. Projected Maximum Dimension of Various Space Systems as a Function of Time (adapted from Hagler et al, 1977)

Contamination of the near-earth environment by photoelectrons is only one of many potentially damaging space system effects on the environment. Contaminant clouds, already discussed in conjunction with degradation of optical and thermal surfaces, also threaten the ambient low-energy plasma environment. Sputtering due to high energy particle impacts, multipacting, chemical exhausts, and, particularly, ion engine exhausts (Luhmann et al, 1978; Chiu et al, 1979) all threaten the status quo. Luhmann et al (1978) have shown (Figure 5) how the deposition of large amounts of argon in the plasmasphere due to solar power satellite operations will result in the conversion of the region from a hydrogen dominated to oxygen dominated region. Finally, large structures will absorb correspondingly large amounts of the ambient flux. Although this will probably be more important for the high energy particle environment, measurable perturbations of the low energy plasma are a possibility if extensive operations at geosynchronous orbit are implemented as planned.

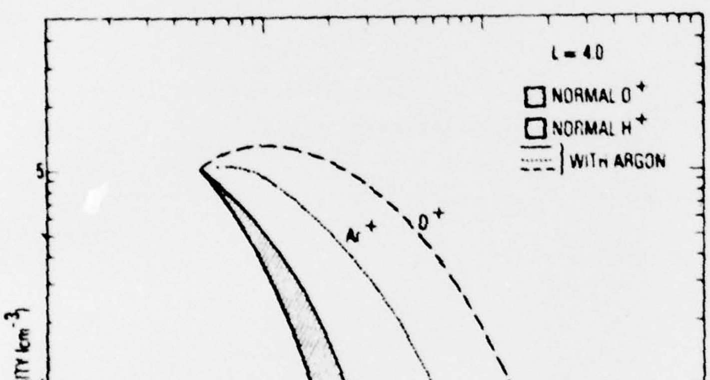

Figure 5. Projected Variations of H^+, O^+, and Ar^+ Before and After the Passage of a Large Solar Power Satellite to Geosynchronous Orbit (Luhmann et al, 1978)

Although several papers on the subject of spacecraft interactions have been referenced, the fact remains that at present relatively little is actually known about most of the interaction processes mentioned. The problem is that there do not as yet exist sufficiently detailed models of many of the dynamic processes associated with the movement of magnetospheric plasma. Similarly, the level of precision necessary to define many of the interactions is severely limited by a lack of experimental data and/or theory. These two problems are not and cannot be divorced from each other as we must define the parameters necessary to accurately represent the environment and at the same time those parameters must be keyed to the interaction models to be of any use. As will become apparent, a real dichotomy exists between the parameters currently used to define the environment and those required to predict plasma interactions.

3. PRESENT STATUS

In order to demonstrate the difficulties attendant with studying the problems of low energy particle interactions with space systems, the current status of these efforts will be reviewed. First, a brief review of the current status of low energy magnetospheric plasma models will be given. This will be followed by a discussion of attempts at predicting and modeling the interaction phenomena associated with the low energy environment. Finally, an example will be given of one attempt to link these three areas into a coherent predictive model of one interaction phenomena—spacecraft charging during eclipse passage.

3.1 Low Energy Plasma Models

In Garrett (1979) the current status of the modeling of the 0-100 keV near-earth particle environment is reviewed in great detail. This section presents some of the main results of that study; the reader is referred to that review for a more detailed description. As in Garrett (1979), comments are confined to the ionospheric and auroral domains as described by Vasyliunas (1972). That is, only the low energy (0-100 keV) charged particle population in the plasmasphere and the near-earth plasma sheet regions will be considered. Also, variations in ionic composition will be ignored (see Young, 1979, for a treatment of ionic composition variations).

Four types of quantitative models are described, dependent upon the ratio of theoretical to empirical input to the model. The most elementary models discussed consist of statistical compendiums of various parameters as functions of space, time, and geomagnetic activity. These statistical models require little theoretical input, relying primarily on actual measurements. Consideration of basic physical

principles makes possible the derivation of analytic expressions capable of simulating changes in the environment—the second type of model. Third are models that employ theory to predict trajectories of particles in static electric and magnetic fields. Finally, the most complete model from a theoretical standpoint is a full, three-dimensional, time-dependent model capable of taking into account time-varying injection events. The following discussion centers on these four categories of models.

Statistical models, as defined here, are compendiums or histograms of various plasma parameters based on actual data. The basic examples of this type of model are the composite or average distribution functions generated by Chan et al (1977) for various magnetospheric and solar wind regions (Figure 6). Although such descriptions are particularly useful in predicting long term fluxes, a prohibitive number of distribution functions are needed as a function of time, spatial coordinates, and geomagnetic activity to adequately describe the near-earth magnetosphere. Instead, a description in terms of the first four plasma moments (density, number flux, pressure or energy density, and energy flux), from which a number of parameters such as current and temperature can be derived, has emerged as a compact means of describing the environment. Vasyliunas (1968), DeForest and McIlwain (1971), Su and Konradi (1977), and Garrett et al (1978b) have all carried out statistical studies of these parameters. In Figure 7, results from the analysis of ATS-5 and ATS-6 temperatures and currents are plotted. As an example, T(AVG) is the temperature obtained from dividing the energy density by the number density; T(RMS) is the temperature obtained from dividing the energy flux by the number flux.

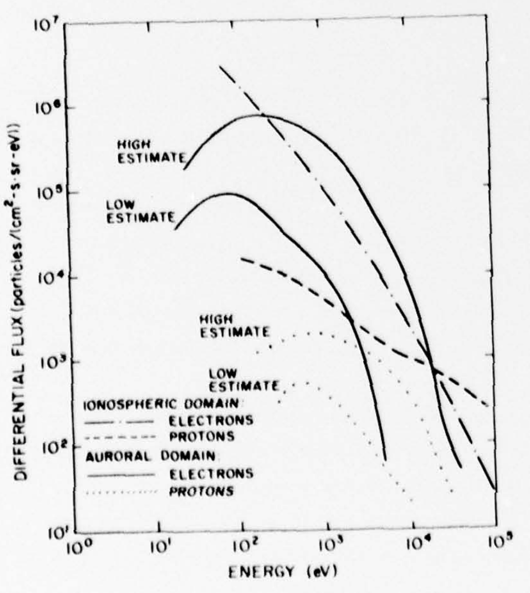

Figure 6. Estimated Differential Particle Fluxes for the Auroral and Ionospheric Domains (from Chan et al, 1977)

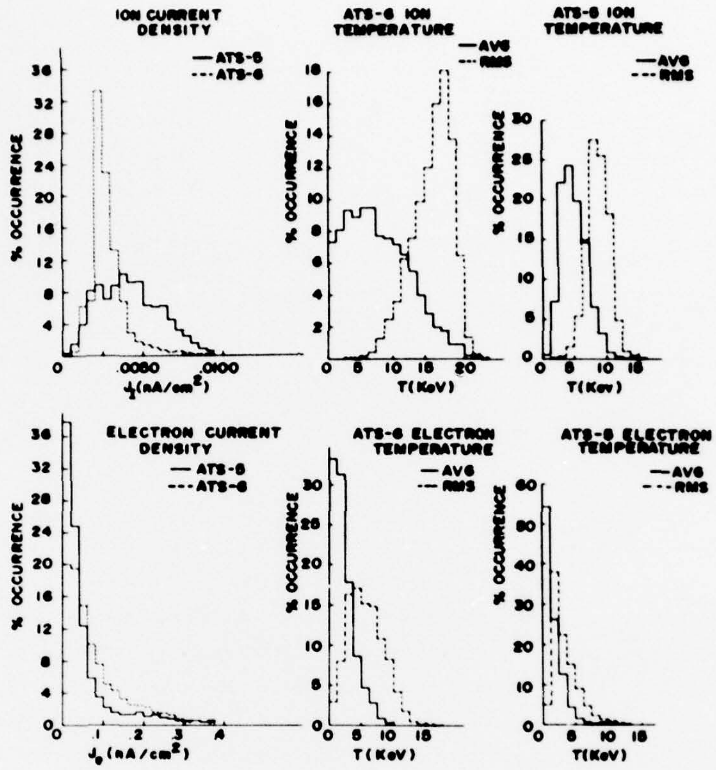

Figure 7. Histograms of the Occurrence Frequencies of the Electron and Ion Temperatures and Current at Geosynchnous Orbit as Measured by ATS-5 and ATS-6. T(AVG) is 2/3's the ratio of energy density to number density; T(RMS) is one-half the ratio of particle energy flux to number flux (Garrett et al, 1978b)

Models have also been developed for other spatial positions by plotting the results from eccentric, inclined satellites in the manner of the intensity plots of high energy particles. A particularly good example is given in Figure 8 (Frank, 1967) for the low energy ions (200 eV $\leq$ E $\leq$ 50 keV) in the generalized R - λ_m coordinate system. Similar studies (Carpenter, 1966; Chappell et al, 1970; Lennartsson and Reasoner, 1978; and reviews by Chappell, 1972, and Carpenter and Park, 1973) of the plasmasphere also exist.

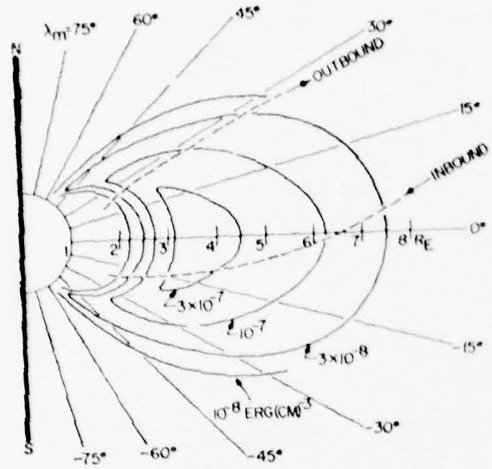

Figure 8. Contours of Constant Proton ($200 \text{ eV} \le E \le 50 \text{ keV}$) Energy Density as Measured by OGO 3 on 9 July 1966 in a $R - \lambda_m$ Coordinate System (Frank, 1967)

The major difficulty with the preceding statistical models from a predictive standpoint is that the effects of complex time variations cannot be included while maintaining the interrelationships between the various parameters. One solution to this problem is simply to provide several detailed but representative examples (see DeForest and Wilson, 1976) of actual spectra. Unfortunately, from a practical standpoint such information lacks compactness and does not easily provide many of the parameters required by potential users. A solution to this problem of tradeoff between accuracy and massive amounts of data has been the introduction of analytical equations capable of modeling specific parameter variations. An example is the well known formula for the midnight-dawn plasmapause of Carpenter and Park (1973) (see also Mauk and McIlwain, 1974; Freeman, 1974; and, particularly, the review of injection boundary formulas by Kivelson et al. 1978):

$$L_{pp} = 5.7 - 0.47\, K_p \tag{1}$$

where L_{pp} is the plasmapause boundary (in earth radii) and K_p is the maximum value of K_p in the preceding 12 hours.

Fairly detailed analytic formulas have been or are being developed for a variety of plasma parameters as functions of time, spatial position, and geomagnetic activity. Su and Knoradi (1977), Garrett (1977), and Garrett and DeForest (1979b) have all developed analytic expressions capable of defining the geosynchronous environment. Garrett and DeForest (1979b) in particular have developed a compact representation in which the first four moments of the distribution function at geosynchronous orbit are expressed in terms of equations linear in A_p (daily average of a_p) and varying diurnally and semidiurnally in local time, LT:

$$M_i(A_p, LT) = (a_o + a_1 A_p)(b_o + b_1 \cos(\frac{2\pi}{24}(LT + t_1)) + b_2 \cos(\frac{4\pi}{24}(LT + t_2)) \quad (2)$$

where

M_i = moment i

$a_o, a_1, b_o, b_1, b_2, t_1, t_2$ = fitted parameters.

Typical results are given in Figure 9. A major advantage of this model is that a two-Maxwellian (that is, the sum of two distinct plasma components) distribution function can be derived directly from the data. Konradi (private communications) is extending this model to lower altitudes and different latitudes.

The previous two model types provide most of the data that are needed to predict environmental effects on space systems. However, to fully understand the effects of space systems on the environment, a rudimentary knowledge of how man-made contaminants and perturbations of the environment propagate in the magnetosphere is required. Thus, static models of the magnetospheric fields play an important role in this review. Unlike the preceding models, considerable work has gone into studying such models, so only a few representative examples will be given here (please see review by Garrett, 1979).

The most typical example of static field models is that developed by McIlwain (1972) in conjunction with the ATS-5 geosynchronous data. By careful analysis of the data, McIlwain constructed electric and magnetic field models that were capable of reproducing the observed spectra. Some results of his analysis for typical electron and ion trajectories in his model fields are given in Figures 10a and 10b. Many variations exist on McIlwain's model, ranging from the early models of Kavanagh et al (1968), Roederer and Hones (1970), to Walker and Kivelson (1975). The major difference between most of these models is the exact treatment of the plasma injection event (see review by Kivelson et al, 1978). The resolution of this problem is dependent on what role the in situ and ionospheric plasma sources play, and is still under study.

The static models of the plasmasphere divide into two principal categories: ionospheric diffusion and $\overline{E}\times\overline{B}$ drift. Chappell et al (1970) and, to a lesser extent, Wolf (1970) and Chen (1970) model the drifts of particles in the plasmasphere in a similar fashion to McIlwain—that is, by $\overline{E}\times\overline{B}$ drift. Others such as Angerami and Thomas (1964), Schunk and Walker (1969), and Mayr et al (1972) model the upward diffusion of ionospheric particles into the exosphere and plasmasphere. Recently, Lemair and Scherer (1974) and Chiu et al (1978) have produced comprehensive models in this latter category by using a collisionless kinetic theory to compute the diffusion along the field line of various constituents.

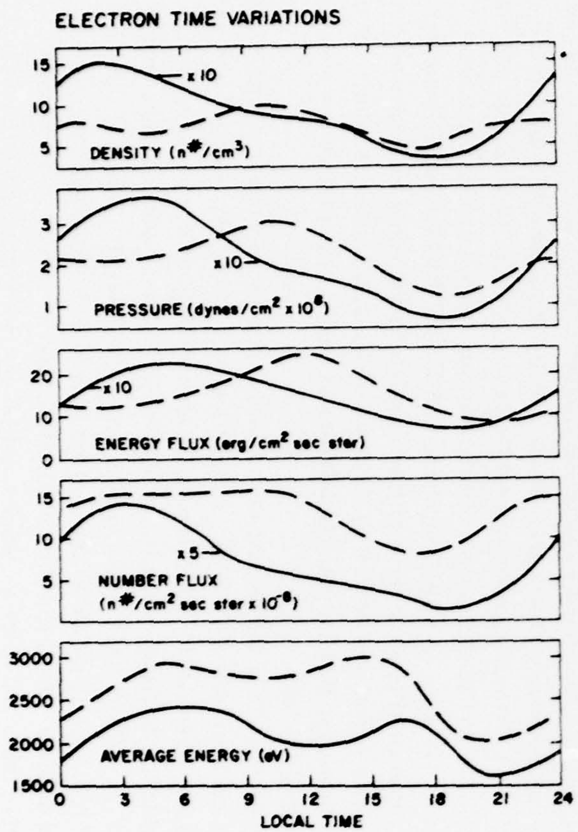

Figure 9a. Electron Parameter Time Variations as a Function of Local Time (Garrett et al, 1979a). The solid line is for $A_p = 15$ and the dashed line for $A_p = 207$

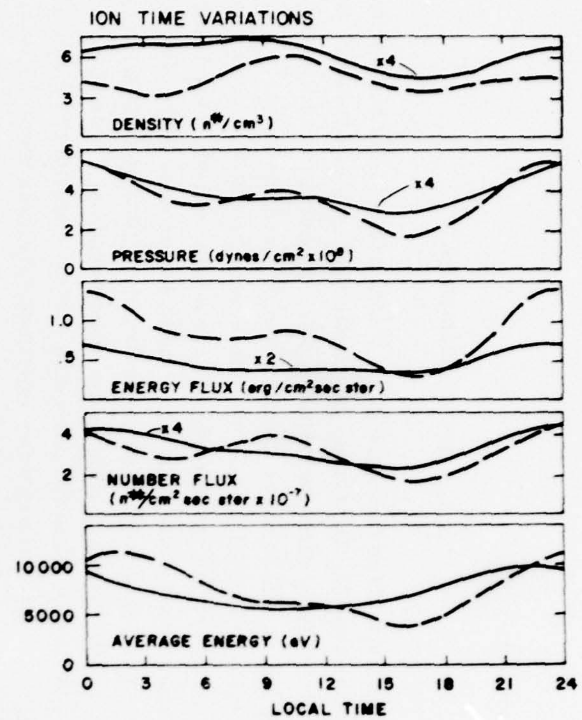

Figure 9b. Ion Parameter Time Variations as a Function of Local Time (Garrett et al, 1979a). The solid line is for $A_p = 15$ and the dashed line for $A_p = 207$

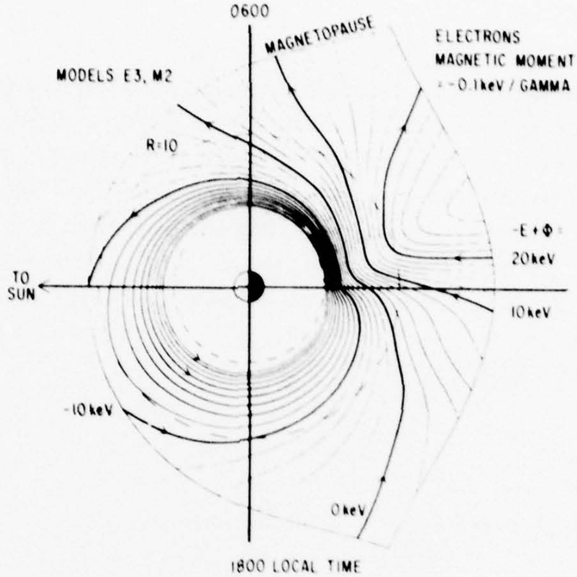

Figure 10a. Trajectories for Electrons Having μ =-0. 1 keV/γ in the McIlwain Model (McIlwain 1972)

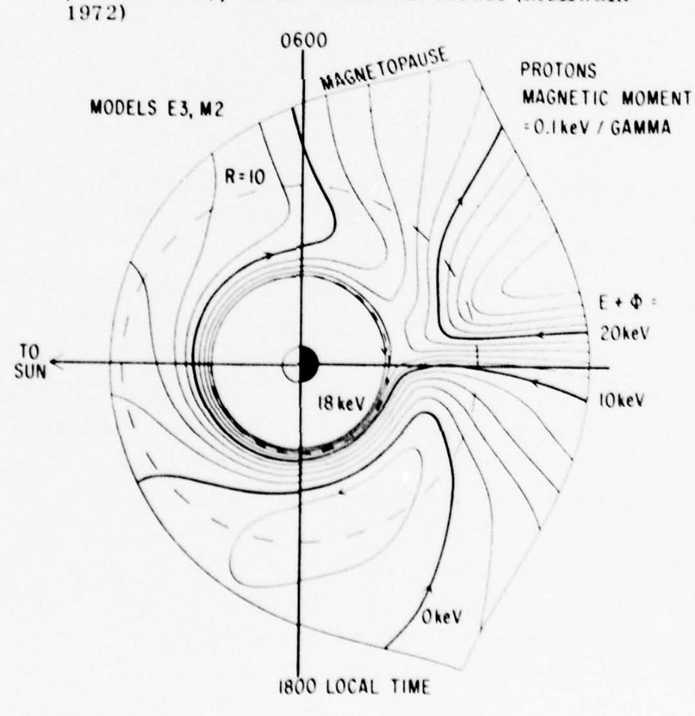

Figure 10b. Trajectories for Protons Having μ = 0. 1 keV/γ in the McIlwain Model (McIlwain 1972)

Although most of the effort in magnetospheric modeling has gone into static models, an increasing amount of detailed work on the time-dependent behavior of the low energy plasma environment has appeared. Specifically, Roederer and Hones (1974) successfully reproduced many of the features of the ATS-5 data by assuming a static field model upon which they superimposed a time-varying electric field component. Similarly, Smith et al (1978a, 1978b, 1979) used a time-varying convection electric field potential ϕ of the Volland-Stern type (Ejiri et al, 1977):

$$\phi = AR^2 \sin\left(\frac{2\pi\, LT}{24}\right) \tag{3}$$

where

LT = local time dependence (0 at midnight)

R = radial distance from earth

and A is taken to be of the form (Grebowsky and Chen, 1975):

$$A = \frac{0.045}{(1 - 0.159\, K_p + 0.009\, K_p^{\,2})^3} \; .$$

Assuming a dipolar magnetic field, Smith et al (1978a, 1978b, 1979) produced a movie of the plasma flow entitled "Convection of Magnetospheric Particles in a Time-Varying Electric Field."

The final models to be discussed are the detailed three-dimensional, time-dependent models of the Rice University group under R. A. Wolf. Chen (1970), Wolf (1970), Chen and Wolf (1972), Jaggi and Wolf (1973), Wolf (1974), and more recently Southwood (1977) and Harel et al (1978) are representative of the Rice work. Unique among magnetospheric models, they calculate the particle drifts and the resulting effects on the electric and magnetic fields in a self-consistent fashion. Some of the Rice results for the magnetosphere (Jaggi and Wolf, 1973) and the plasmasphere (Chen and Wolf, 1972) are presented in Figures 11a, 11b, and 11c. Note in particular how the plasma "tails" off from the plasmasphere. As this phenomena represents a loss mechanism for the plasmasphere, it may be important for calculations of contaminant lifetimes in this region.

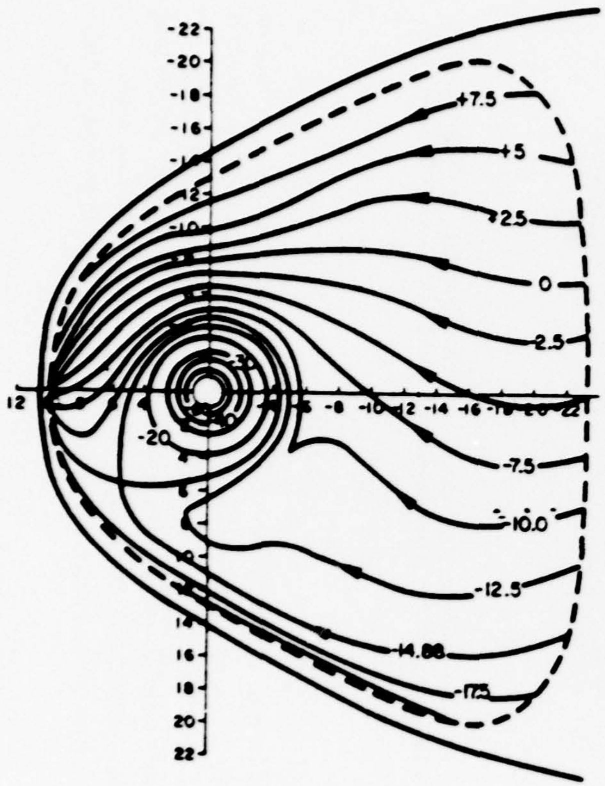

Figure 11a. The Electrostatic Potential 6 Hours After a Sheet of Ions Started Moving Toward the Earth From the Magnetospheric Tail (Jaggi and Wolf, 1973)

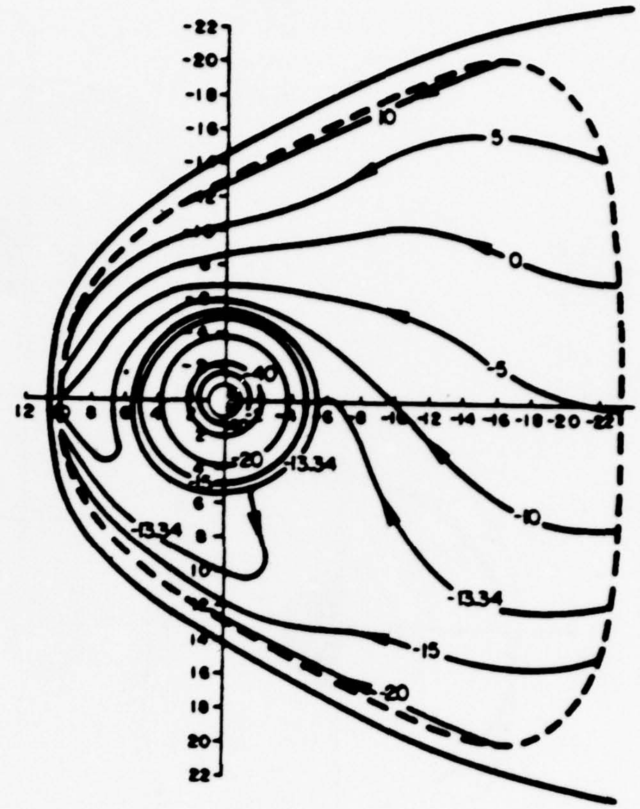

Figure 11b. The Electrostatic Potential 15 Hours After the Sheet Started Moving Towards the Earth From the Magnetospheric Tail (Jaggi and Wolfe, 1973)

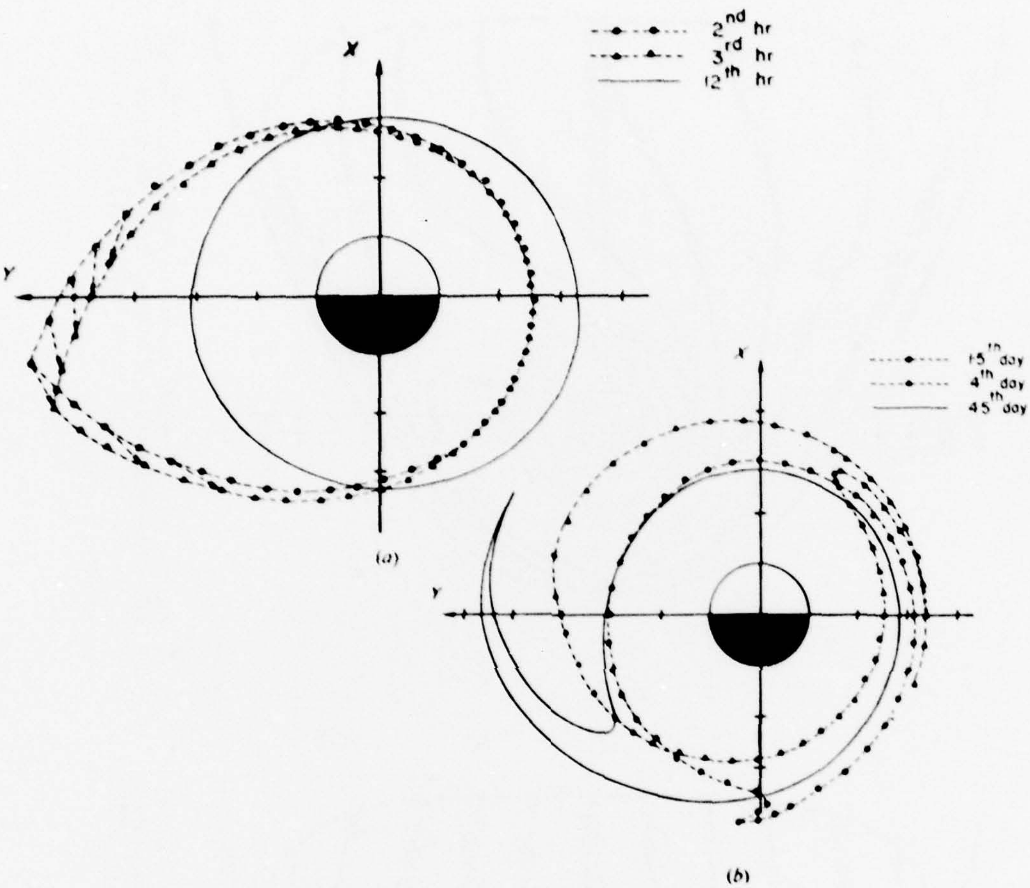

Figure 11c. The Distortion of the Plasmapause at Various Times Following a Factor of 2 Decrease in the Convection Field at Time t = 0 (Chen and Wolf, 1972)

3.2 Interaction Modeling

Modeling or prediction of interactions with the low-energy plasma environment is regarded by many as synonymous with spacecraft charging. Therefore, most of the discussion in this section is concerned with current efforts at modeling the charging phenomena and related problems such as contaminant effects. In the long term, however, the prediction of environmental effects will probably be more critical. Thus, the final part of this section briefly reviews the work done in this area to date.

Spacecraft charging is, simply, the coming to equilibrium of the currents to the spacecraft surface:

$$J_E - (J_I + J_{SE} + J_{BSE} + J_{PH} + J_X) = 0 \tag{4}$$

where

J_E = incident electron current,

J_I = incident ion current,

J_{SI} = secondary electron current due to ions,

J_{SE} = secondary electron current due to electrons,

J_{BSE} = backscattered electron current,

J_{PH} = photoelectron current (zero when a surface is shadowed),

J_X = thruster currents and other miscellaneous currents (normally assumed to be zero in simple calculations).

All of the currents are complex functions of spacecraft potential, the satellite plasma sheath (the region over which the satellite perturbs the ambient medium), the satellite materials, and the physical structure of the satellite. Several models (see Whipple, 1965; Rothwell et al, 1977; Laframboise and Prokopenko, 1977; Parker, 1977; and references therein) carry out fairly detailed calculations of the particle trajectories in the vicinity of a satellite, allowing simulations of the sheath and differential potentials. A variety of simple single point (or "thick sheath") models also exist which allow an approximate calculation of the equilibrium potential on a spacecraft (see Garrett and Rubin, 1978, and references therein). These models have been extended by the inclusion of equivalent resistances and capacitances (Inouye, 1976; Massaro et al, 1977; Gauntt, 1979) to actually allow the simulation of the time response of satellites to changes in the ambient particle and photon environment.

In all of the above, the detailed shape of the sheath around the spacecraft is not calculable except for some rather simple geometries. Recently, however, a detailed computer code capable of simulating a complex satellite, including booms and shadowing, has been developed (Katz et al, 1979). The results from one of these calculations is presented in Figure 12 where the potentials around a simulation of the SCATHA satellite are plotted. The code is currently undergoing intensive comparison with data from laboratory experiments and from the SCATHA satellite. It is planned that in the next year the program will be sufficiently reliable to accurately model the diverse effects of spacecraft charging.

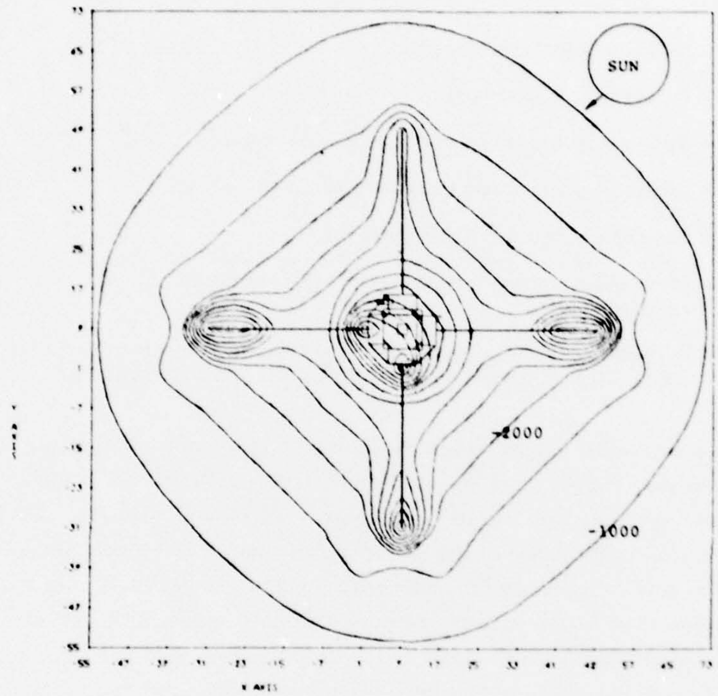

Figure 12. Potential Contours for Sunlit Case in a Horizontal Plane Through the SCATHA Satellite Center. Contours are at 500 V steps (the minimum is -7500 V). From Schnuelle et al (1979)

Other critical aspects of the spacecraft charging phenomenon are the effects on contaminants and the effects of discharges. Since insulators tend to charge to different potentials than the satellite as a whole, it is possible to get preferential deposition of contaminant ions on such critical surfaces as optical sensors and solar cell covers (see Cauffman, 1973, for analysis of contamination rates). Likewise, arcing due to differential charging is apparently well documented (Figure 13). Although the actual arcing process itself is poorly known, fairly sophisticated models exist of the effects of the resultant electromagnetic pulse (Mindel, 1977).

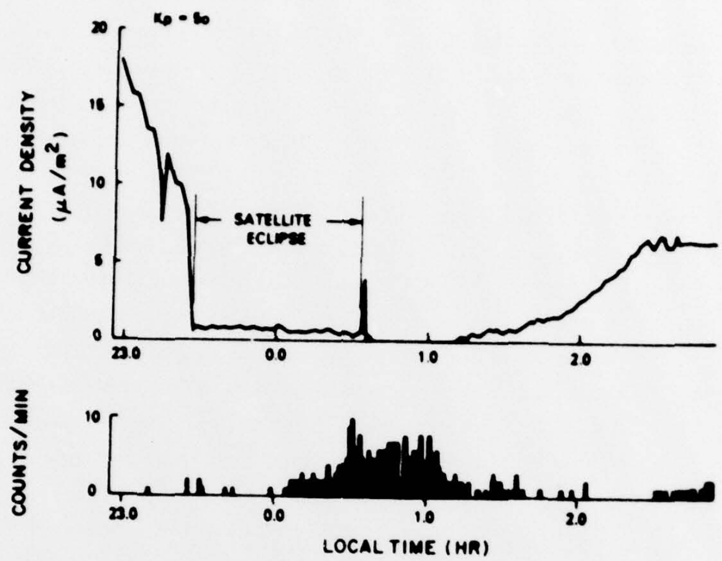

Figure 13. Arc-discharge Rate and Photoelectron Current Density as a Function of Local Time During Eclipse Passage. The depression in the photoelectron current following eclipse passage is a result of spacecraft charging associated with a substorm injection event. Thus the increased discharge rate is believed to be related to geomagnetic activity. From Shaw et al (1976)

As the emission of photoelectrons could be a potentially important source of contamination and has a significant impact on charging, a brief review is in order. Although the process of photoemission has been well understood since Einstein's original paper, the actual emission rates for satellite materials are, in practice, not well known. Grard (1973) has made an extensive analysis of such phenomena. His results for common materials are presented in Table 1. Garrett and Rubin (1978) and Garrett and DeForest (1979a) have attempted by increasingly more sophisticated theories to predict the effects of a varying photoelectron flux. A typical result is given in Figure 14 demonstrating how the satellite potential can vary by 10 kV in a matter of a minute. As previously discussed, the escape rate (as opposed to emission rate) for photoelectrons appears to be 0.4 nA/cm^2, a number larger on the average than that of the ambient flux of electrons at geosynchronous orbit (Garrett, 1977). The effect of such fluxes from large space structures on the environment has not been calculated.

Satellites are known to generate wakes (Parker, 1977) that in turn could generate waves in the magnetospheric plasma. The large space structures currently planned could generate significant wave disturbances that might lead to instabilities

in the low energy plasma environment. Parker (1977) and Douglas et al (1977) have advanced simple models of this phenomenon. For example, in Douglas et al (1977), the waves are envisioned as interacting with the structure itself (that is, the solar sail), leading in some cases to resonance between the structure and the waves.

Another source of contamination is the addition of argon and other ionized gases from extensive space operations. A model of argon emission in the ionospheric domain advanced by Luhmann et al (1978) has already been mentioned. Briefly, $\sim 1.5 \times 10^{31}$ Ar^+ ions (compared with $\sim 4 \times 10^{31}$ ambient ions at about 500 km) are emitted as a solar power satellite slowly spirals out to geosynchronous orbit. The argon ions require a corresponding electron population for charge neutrality. Eventually, the heavy argon ions sink back into the ionosphere. As insufficient hydrogen ions exist to replace the argon, oxygen is drawn upwards, giving the behavior illustrated in Figure 5.

Vondrak (1977, 1979) presented a simple model of the leakage of neutral particles in the magnetosphere. Depending on the constituent, ionization rates on the order of hours to days could result in the slow buildup of a neutral gas ring followed, at equilibrium, by the addition of charged particles to the plasmasheet flow. As discussed in Vondrak (1979), the total mass flow rate for the plasma sheet is only on the order of 1.2 kg/sec. The artificial addition of charged particles due to ion thrusters and/or a neutral gas ring (with subsequent ionization) could equal or be greater in magnitude than this flow rate. No detailed models for the effects on the auroral (plasmasheet) domain yet exist, however.

Table 1. Photoelectron Emission Characteristics of Various Spacecraft Materials (Grard, 1973)

Material	Work Function (eV)	Electron Saturation Current (10^{12}/sec m^2)	Saturation Current Density ($\mu a/m^2$)
Aluminum Oxide	3.9	260	42
Indium Oxide	4.8	190	30
Gold	4.8	180	29
Stainless Steel	4.4	120	20
Aquadag	4.6	110	18
LiF on Au	4.4	90	15
Vitreous Carbon	4.8	80	13
Graphite	4.7	25	4

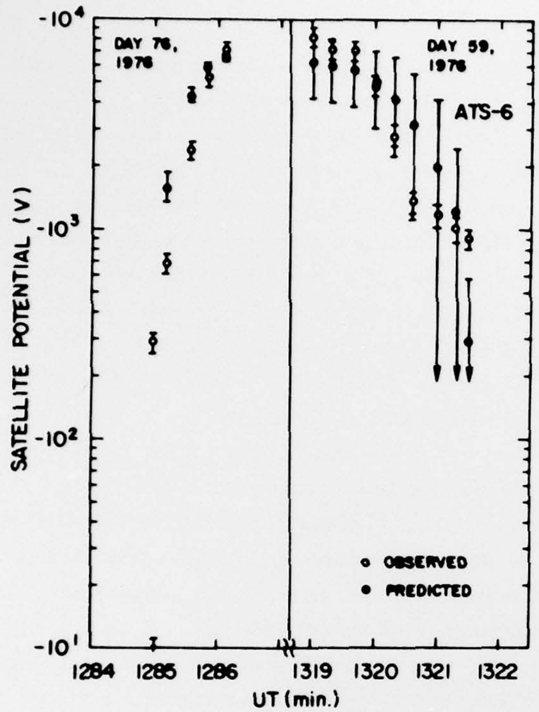

Figure 14. Observed and Predicted Potential Variations on ATS-6 During Passage Through the Earth's Penumbra (Garrett and DeForest, 1979a)

3.3 Magnetospheric Predictions

The preceding two sections outlined the status of models of the plasma environment and of the various types of interactions. Since the purpose of this report is the status of predictions, the review cannot be complete without a description of the relevant models used for predicting the environmental parameters needed to estimate low energy particle interactions. These models fall into three areas: predictions of magnetospheric, magnetic, and electric field; direct predictions of ambient plasma parameters; and predictions of geomagnetic indices. The use of real-time in situ data is discussed in a later section.

Considering the availability and sophistication of magnetic field models (Olsen and Pfitzer, 1979), it is possible to make a reasonable approximation to these fields. Unfortunately, most magnetic field models are either for quiet periods or dependent on K_p or a_p, earth-based indices. Likewise, the electric field models, such as that of Eq. (3), are all based on geomagnetic indices. Given the fields by any of these predictive methods or by actual in situ measurements, one could in principle predict the evolution of the plasma fluxes in time and space, using the static or time-dependent models discussed previously. Once the fluxes are known, the interactions can be predicted.

Although the preceding technique is probably the most scientifically preferable method as it allows a consistent development of a prediction procedure for the ambient fluxes, it does not necessarily assure accurate predictions. The direct prediction of plasma parameters is to be preferred for modelling satellite interactions as the number of assumptions (that is, particle drift, particle losses, etc.) are significantly reduced. Again, however, some means must be devised to determine the state of the magnetosphere. Even in the case of the simplest model, that of Chan et al (1977), some input is required to tell how often to use the high or low profile. The models of Su and Knoradi (1977) and Garrett and DeForest (1979b) both require knowledge of K_p or a_p. As yet, there is no way to predict geosynchronous plasma parameters from interplanetary parameters.

The following indicates that no matter where one starts, the prediction of geomagnetic indices is the primary means of determining spacecraft interactions. In fact, as indicated in Figure 3 for the rate of arcing and in Figure 15 for the eclipse potential on ATS-5 and ATS-6, it may be possible to directly predict satellite interactions from ground-based indices. The prediction of geomagnetic indices of course depends primarily on persistence or solar wind parameters. A variety of studies have sought to correlate the various measured solar wind parameters, such as velocity, density, temperature, and magnetic field, with geomagnetic activity (Schatten and Wilcox, 1967; Ballif et al, 1967; Hirshberg and Colburn, 1969; Arnoldy, 1971; Foster et al, 1971; Kane, 1972; Garrett, 1974; Garrett et al, 1974; Bobrov, 1973). These previous studies concentrated primarily on correlations with a_p, K_p, Dst, and AE. An example of the adequacy of such models is illustrated in Figure 16 from Garrett et al (1974). Most subsequent studies have essentially refined these early studies (see for example, Garrett et al, 1978a). More recent papers based on similar prediction schemes are those of Saito (1979); Clauer and McPherron (1979), and Iyemori and Maeda (1979). It would be hoped that eventually a strong solar wind-magnetospheric plasma prediction scheme would also be found, but as yet this has not happened.

The conclusion of all the preceding studies is that significant correlations do exist between measured solar wind quantities and the geomagnetic variations observed an hour to a few hours later. It still remains true, however, that persistence (that is, if a_p is a given value now it will be the same in an hour) is a much better predictor in the time range of 0 to 10 hours than any of the solar wind quantities so far studied (Garrett et al, 1978a). Thus, in order to predict spacecraft interactions with any degree of confidence at present, actual ground-based measurements (in lieu of in situ solar wind measurements) remain the most profitable prediction scheme. It remains to be determined, however, what the "best" geomagnetic parameter is for a given interaction process.

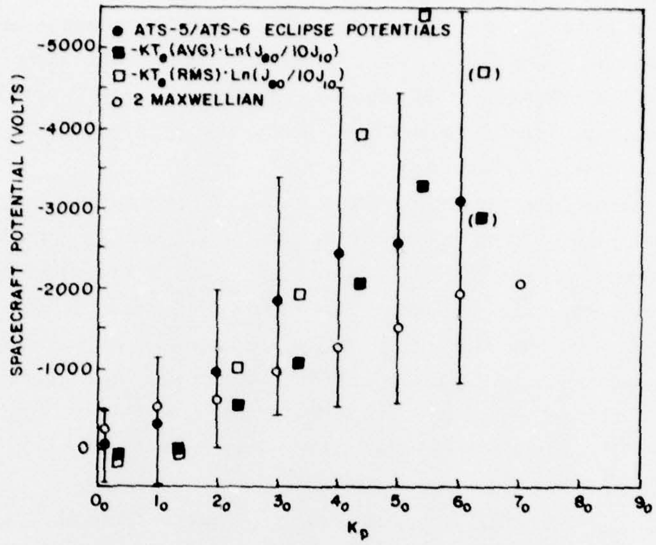

Figure 15. Observed and Predicted Potential Variations With K_p for ATS-5 and ATS-6 While in the Earth's Shadow (Garrett et al, 1979a)

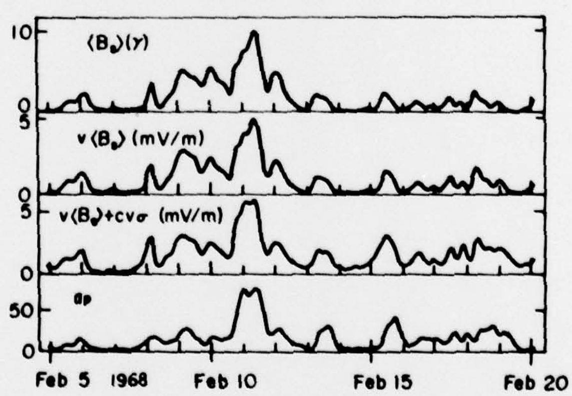

Figure 16. Relationship Between Various Solar Wind Parameters and Geomagnetic Activity as Measured by a_p (Garrett et al, 1974). $\langle B_s \rangle$ is the southward component of the interplanetary magnetic field in solar magnetospheric components, V the solar wind velocity, and σ the magnetic field variance

3.4 Representative Example

In Garrett el at (1979a) an explicit example of the procedures outlined above has been worked out. Although it is not intended to repeat the paper here, the general procedures outlined in that paper demonstrate a typical problem and solution in predicting spacecraft interactions. From that standpoint, the findings of the paper will be briefly reviewed.

An important problem in spacecraft charging is the prediction of the extreme potential stresses likely to be encountered. As the largest measured potentials have been observed between the ATS-5 and ATS-6 geosynchronous satellites during eclipse passage, these data represent a useful starting point for estimating extreme potential effects (in reality, the satellite to space potential during eclipse may well be an accurate reflection of the maximum differential potentials between two electrically isolated surfaces—one that is shadowed and one that is illuminated). In Garrett et al (1979a), the eclipse potentials for seven eclipse seasons of ATS-5 and ATS-6 were carefully measured and plotted as a function of K_p. These results are plotted in Figure 15 as closed dots with error bars. This plot obviously serves as a simple predictive model.

Two charging theories were advanced by Garrett et al (1979a) to explain the charging phenomenon based on ambient plasma parameters. The simplest was based on the formula

$$/q\,V_o/ \simeq -KT_e \ln (J_{E0}/10\,J_{I0}) \qquad (5)$$

where

q = electronic charge,

V_o = satellite potential in volts,

T_e = electron temperature,

J_{E0} = ambient electron current,

J_{I0} = ambient ion current,

K = Boltzmann's constant.

Likewise, two models of the environment were advanced. One was based on statistical tabulations of T_e, J_{E0}, and J_{I0} versus K_p, and the other was based on the variation of the distribution function at ~0130 local time with K_p (based on the model described in Eq. (2) and plotted in Figure 9). The two environmental models, both keyed to K_p, were then combined with the potential prediction codes to estimate the potential as a function of K_p. The results are plotted in Figure 15 and represent good agreement between theory and observation.

4. FUTURE RESEARCH

Considering the potential importance of models of interactions between spacecraft and the environment, it is a significant fact that only in the last 2 or 3 years have attempts been made to accurately define the ambient low-energy plasma environment. Further, it has been only since the recent launch of the SCATHA satellite that any significant attempt has been made to characterize the interaction processes. Thus, it is not difficult to find many inadequacies in the present state of spacecraft/environment interaction prediction.

Surprisingly, much data dc exist on the low-energy near-earth environment—data that are yet to be exploited to any great degree. The geosynchronous orbit is, on the whole, quite adequately covered and, with instruments capable of measuring ionic composition and field aligned fluxes on GEOS I, GEOS II, and SCATHA, this region should soon be well analyzed. The problem is still, however, how best to characterize this rapidly varying regime for real-time predictions. In Garrett et al (1979b), data from ATS-6 and the geosynchronous satellite 1976-059A are compared. The 1976-059A returns in real time the electron fluxes from 30 keV to 300 keV (Higbie et al, 1979). This information appears adequate for predicting the current state of the magnetosphere (Higbie et al, 1979; Baker et al, 1979) to the degree necessary to predict spacecraft charging. Thus, such real time measurements may offer one possible solution to the prediction problem for geosynchronous orbit (see also Thompson and Secan, 1979). The issue for the plasmasphere and near-earth high latitude region is not as clear-cut. Although sufficient data apparently exists for the equatorial plasmasphere to construct meaningful statistical models, developments in this area have not been forthcoming. Recently, a tremendous amount of data for detailed studies of the low energy particle fluxes at high latitudes has become available from the S3-2, S3-3, and the electrostatic analyzers on the DMSP satellites (Burke et al, 1979). It is hoped that this data base will soon make possible significant advances in our understanding of this region. The DMSP photos may ultimately provide a real time method of evaluating rapid variations in this region, as 1976-059A may for geosynchronous orbit. Likewise, ISEE-3 and OPEN-A may allow real time solar wind monitoring (Cauffman, 1979).

From a user standpoint it is of critical importance that accurate statistical models be available in the future if any long term mission planning is to be carried out. Likewise, the user will need adequate models of the interaction phenomena involved. Further, little progress can be made in the future in predicting for the user spacecraft/environment interactions if the required parameters are unknown. It does little good to provide detailed information on the energy flux if the interaction process is dependent on number flux. Unfortunately, the biggest gap in this area is in spacecraft material response functions. Although not considered in this

report, until it is resolved, the only part of the spacecraft/interactions problem that we can accurately attack is the ambient space environment and its perturbations.

Predicated on the following it appears that future research should be directed in the following main areas:

1. Defining in a statistical sense the ambient environment based on user requirements (particularly the near-earth plasmasphere and at high latitudes).

2. Deriving analytical expressions or efficient three-dimensional models (static and time-dependent) capable of simulating magnetospheric variations for input into interaction modeling programs.

3. As it currently appears that predictions based on earth-based or solar wind parameters will not approach the accuracy of in situ measurements, expanded real time, in situ measurements must be made.

4. Verification of particle drift theory so that static (or time-dependent) models can be used to extend measurements made in limited orbital regions to other regions.

5. Refinement of our basic understanding of interaction phenomena.

In the next few years, major steps will be made in all these areas. Active experiments such as barium releases and joint SCATHA/GEOS beam propagation studies in the magnetosphere should greatly improve our ability to trace contaminant clouds. Likewise, the Long Duration Exposure Facility (LDEF) should provide important information on the long term effects of the environment. Support of the AF/DoD community should be given to projects such as these, as they promise immediate, practical returns from scientific studies.

5. CONCLUSION

In this review the present state of spacecraft/environment interactions modeling and prediction as it pertains to the low energy plasma environment has been covered. Several issues have been raised in each of the main areas: modeling of the interaction process, modeling the environment, and predicting the future state of the magnetosphere (and, hence, the magnitude of the interaction). As should be apparent, the status of the modeling efforts is still somewhat rudimentary; the most successful efforts were the development of static models of the magnetosphere, the least successful were the determination of material responses. The role of the user has has had little to do in determining the research trends in this area as it has only comparatively recently been realized that spacecraft/environment interactions were of real importance. As more emphasis is placed on user needs, however, we should expect a shift to more basic models of the environment (that is, statistical models like those of the radiation environment). Ultimately, however, three-dimensional, time-dependent models will be necessary if a complete understanding is desired. In the interim, in situ, real-time monitoring appears to be the only plausible solution.

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